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# MOLECULAR GAS IN A SUBMILLIMETER GALAXY AT $z = 4.5$: EVIDENCE FOR A MAJOR MERGER AT 1 BILLION YEARS AFTER THE BIG BANG[1]

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## ABSTRACT

We report the detection of CO molecular line emission in the $z = 4.5$ millimeter-detected galaxy COSMOS J100054+023436 (hereafter J1000+0234) using the IRAM Plateau de Bure interferometer (PdBI) and NRAO's Very Large Array (VLA). The $^{12}$CO(4–3) line as observed with PdBI has a full line width of ∼1000 km s$^{-1}$, an integrated line flux of 0.66 Jy km s$^{-1}$, and a CO luminosity of $3.2 \times 10^{10}\ L_{\odot}$. Comparison to the 3.3 $\sigma$ detection of the CO(2–1) line emission with the VLA suggests that the molecular gas is likely thermalized to the $J =$ 4–3 transition level. The corresponding molecular gas mass is $2.6 \times 10^{10}\ M_{\odot}$ assuming an ULIRG-like conversion factor. From the spatial offset of the red- and blueshifted line peaks and the line width a dynamical mass of $1.1 \times 10^{11}\ M_{\odot}$ is estimated assuming a merging scenario. The molecular gas distribution coincides with the rest-frame optical and radio position of the object while being offset by 0.5″ from the previously detected Ly$\alpha$ emission. J1000+0234 exhibits very typical properties for lower redshift ($z \sim 2$) submillimeter galaxies (SMGs) and thus is very likely one of the long sought after high-redshift ($z > 4$) objects of this population. The large CO(4–3) line width taken together with its highly disturbed rest-frame UV geometry suggest an ongoing major merger about a billion years after the big bang. Given its large star formation rate (SFR) of >1000 $M_{\odot}$ yr$^{-1}$ and molecular gas content this object could be the precursor of a "red and dead" elliptical observed at a redshift of $z = 2$.

*Subject headings:* galaxies: formation — galaxies: high-redshift — galaxies: ISM — galaxies: starburst — submillimeter

## 1. INTRODUCTION

Wide-field blank-sky surveys at millimeter and submillimeter wavelengths have established a population of active star-forming galaxies at high redshift (e.g., Blain et al. 2002). These sources or so-called submillimeter galaxies (SMGs) dominate the (sub)millimeter background, and represent (50–75)% of the star formation at high redshift causing a significant revision to the optically derived star formation history of the universe (Smail et al. 1997; Hughes et al. 1998; Barger et al. 1998; Bertoldi et al. 2000).

The bulk of this population lies at redshifts below $z = 3$, with far-infrared (FIR) luminosities of $\geq 10^{13}\ L_{\odot}$, which (if powered by star formation) imply star formation rates in excess of 1000 $M_{\odot}$ yr$^{-1}$. This is sufficient to build up the stellar mass of a giant elliptical galaxy in about 1 Gyr (Chapman et al. 2005). At redshifts $z \leq 3$ about 100 SMGs are now known, many of which have been studied in detail, including CO observations that indicate that they are very massive systems (Greve et al. 2005). Recent high-resolution studies of the molecular gas in $z \sim 2$–3 SMGs (Tacconi et al. 2006, 2008) showed that the star-forming regions are fairly compact and that the SMGs resemble "scaled-up and more gas-rich versions" of the local ultraluminous infrared galaxies (ULIRGs; e.g., Downes & Solomon 1998). Due to their derived central densities, which are close to those of ellipticals or massive bulges, they appear to form stars at the maximal rate over very short timescales ("maximum starburst"). Thus the SMGs phase appears to last for about 100 Myr (Tacconi et al. 2008). These massive starburst galaxies place tight constraints on galaxy formation models (e.g., Baugh et al. 2005). One major focus of current and future (sub)mm surveys is to identify these massive starbursts at $z > 3$, a redshift range for which SMGs could place tight constraints on hierarchical merger versus monolithic collapse models in galaxy formation scenarios.

The discovery of such an SMG above a redshift of $z = 4$ indicates that massive galaxy formation is already well underway when the universe is only 1.5 Gyr old. The recently discovered object J1000+0234 originally selected as a $V$-band drop-out with a weak radio counterpart (Carilli et al. 2008) and with a stellar mass of $M_{*} > 10^{10}\ M_{\odot}$, a young starburst age of 2–8 Myr, and a star formation rate of SFR > 1000 $M_{\odot}$ yr$^{-1}$ is a candidate for such a $z > 4$ SMG, as it was detected in its FIR continuum (Capak et al. 2008). Throughout this Letter we assume a standard concordance cosmology ($H_0 = 70$, $\Omega_M = 0.3$, $\Omega_{\Lambda} = 0.7$).

## 2. OBSERVATIONS

The bolometer camera MAMBO-2 at the IRAM 30 m telescope was used in on-off mode in 2007 December and 2008 January to measure the 1.2 mm flux density of J1000+0234. The weather conditions during the observations were good, and the reduction was performed using MOPSIC (written by R. Zylka, IRAM). The achieved rms for a total on-sky integration

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TABLE 1
Properties of J1000+0234

| Property | Value | Comment |
|---|---|---|
| $S_{250\ \mathrm{GHz}}$ (mJy) | 3.4 ± 0.67 | MAMBO |
| $S_{83\ \mathrm{GHz}}$ (mJy) | 0.2 ± 0.09 | Off-line channels (~2 $\sigma$, PdBI) |
| $S_{42\ \mathrm{GHz}}$ (mJy) | ≤0.15 | Off-line channel (≤3 $\sigma$, VLA) |
| $z_{\mathrm{CO(4-3)}}$ | 4.542 | Center of CO(4–3) line |
| $\mathrm{FWZI_{CO(4-3)}}$ (km s$^{-1}$) | ~1000 | CO(4–3) line |
| $S_{\mathrm{CO(4-3)}}$ (Jy km s$^{-1}$) | 0.66 ± 0.12 | 5.5 $\sigma$ detection (PdBI) |
| $S_{\mathrm{CO(2-1)}}$ (Jy km s$^{-1}$) | 0.057 ± 0.017[a] | 3.3 $\sigma$ detection[b] (VLA) |
| $\mathrm{R.A._{CO(4-3)}}$ (J2000.0) | $10^{h}00^{m}54.484^{s}$ | Line peak |
| $\mathrm{Decl._{CO(4-3)}}$ (J2000.0) | +02°34′35.73″ | Line peak |
| $L'_{\mathrm{CO}}$ ($L_{\odot}$) | $3.2 \times 10^{10}$ | From CO(4–3) |
| $M_{\mathrm{gas}}$ ($M_{\odot}$) | $2.6 \times 10^{10}$ | From CO(4–3) |
| $M_{\mathrm{dyn}} \times \sin^2 i$ ($M_{\odot}$) | $1.3 \times 10^{11}$ | Using FWZI and $r$ = 0.5″ |

Note.—Some properties measured from our PdBI and VLA data and derived using the equations given by Solomon & Vanden Bout (2005) and Neri et al. (2003).

[a] Observed line flux not corrected for small bandwidth (see text for details).

[b] Available bandpass corresponds to $\Delta v \approx 360$ km s$^{-1}$, i.e., a third of the total line width.

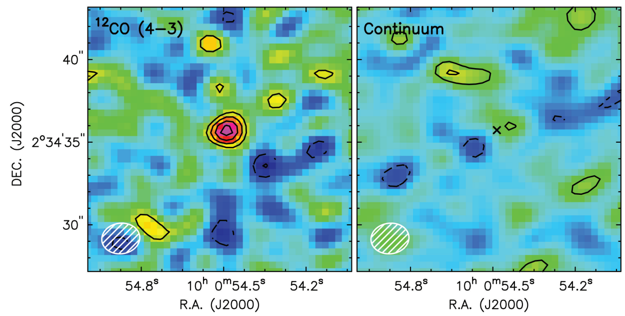


Fig. 1.—CO(4–3) line emission and corresponding continuum in J1000+0234 as observed with the PdBI, shown on the same color scale, but with different contour levels. Continuum emission from J1000+0234 is detected at the 2 $\sigma$ level, while the emission from the CO(4–3) line shows a solid detection at 5.5 $\sigma$. The integrated CO(4–3) line emission (*left*) is centered at a velocity of +500 km s$^{-1}$ relative to the observed frequency of 83.3257 GHz. Contours start at 2 $\sigma$ in steps of 1 $\sigma$ with 1 $\sigma$ = 0.12 Jy beam$^{-1}$ km s$^{-1}$. The integrated continuum (*right*) has the same contour steps; however, 1 $\sigma$ corresponds to 0.08 mJy beam$^{-1}$. The cross indicates the position of the CO(4–3) peak. The beam is shown in the lower left corner.

of 70 minutes is 0.67 mJy. J1000+0234 was detected at a 5 $\sigma$ level with a total 1.2 mm continuum flux density of 3.4 mJy.

The $^{12}$CO(4–3) line tracing cold molecular gas in J1000+0234 was observed with the IRAM Plateau de Bure interferometer (PdBI) between 2008 January and April in the special C and C configurations. Both receivers were tuned to the redshifted line frequency of 83.3257 GHz covering a total bandwidth of ~0.9 GHz. For calibration and mapping, we used the standard IRAM GILDAS software packages CLIC and MAPPING (Guilloteau & Lucas 2000). The quasar 1005+058 was used for atmospheric calibration while standard calibrators were used for flux calibration. The 12 hr of total integration time result in a data cube of 2.3″ × 1.9″ resolution (using robust weighting) with an rms of 0.42 mJy beam$^{-1}$ for 20 MHz (~72 km s$^{-1}$) wide channels.

We used the VLA in D configuration to observe the $^{12}$CO(2–1) line in 2008 June and July for a total of 21 hr. The two 50 MHz wide correlator units (each corresponding to a velocity width of ~360 km s$^{-1}$) were tuned to 41.6352 GHz (on-line) and 41.7351 GHz (off-line). The observations were done in the fast-switching mode using the nearby quasar 1018+055, at a distance of 5.3° from our source, for atmospheric amplitude and phase calibration. Twenty antennas were available during the observations and the phase stability was typically ~10°. The final images using natural weighting have a resolution of 1.9″ × 1.4″ and an rms of 49 $\mu$Jy beam$^{-1}$.

All observed and derived properties of J1000+0234 are summarized in Table 1.

## 3. THE MOLECULAR GAS PROPERTIES

The CO(4–3) line was detected at a 5.5 $\sigma$ level (Fig. 1) in a 280 MHz wide channel, which corresponds to a full line width at zero intensity (FWZI) of ~1000 km s$^{-1}$, i.e., with an integrated flux of 0.66 Jy km s$^{-1}$. The peak position of the CO(4–3) emission (see Fig. 2) agrees very well within the positional uncertainties with the rest-frame near-IR and radio position derived by Capak et al. (2008). The line emission of CO(4–3) is centered at an observed frequency of 83.1857 GHz, which corresponds to a redshift of $z$ = 4.5423 [assuming a rest frequency of 461.040768 GHz for $^{12}$CO(4–3)]. Given the large line width this is in agreement with the optically derived redshift of $z$ = 4.547 ± 0.002 (Capak et al. 2008). The CO(4–3) emission coincides with the rest-frame optical counterpart (as traced by the IRAC data) of J1000+0234 (Fig. 2). Averaging the remaining channels blue- and redward of the detected line emission results in a line-free image of 620 MHz width (~2200 km s$^{-1}$) with a tentative 2.2 $\sigma$ detection of the continuum at the rest-frame optical/radio position of the source (Fig. 1).

The VLA observations with a channel width of ~360 km s$^{-1}$ are centered at the middle of the line detected in CO(4–3). CO(2–1) line emission is detected at the 3.3 $\sigma$ level and coincides spatially with the CO(4–3) emission within its positional uncertainties of $\mathrm{FWHM_{beam}}$/(S/N) ~ 0.5″. Only about a third of the total line width was covered during the VLA observations, so the detected line flux of 0.057 Jy km s$^{-1}$ could be higher by a factor of ~3, taking the missed blue- and redshifted emission into account by assuming a boxcar line shape. The ratio of the CO(4–3) line flux of 0.66 Jy km s$^{-1}$ to the thus corrected CO(2–1) line flux of ~0.16 Jy km s$^{-1}$ is about 4, implying that the molecular gas is still thermalized at the $J$ = 4–3 transition, as the flux still increases with $\nu^2$ at this transition.

Continuum emission from J1000+0234 was detected at 1.2

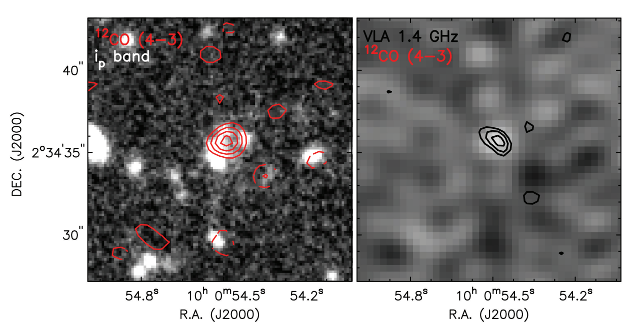


Fig. 2.—Location of the molecular gas relative to other tracers. *Left*: The CO(4–3) line intensity overlaid in contours (same as in Fig. 1) on the Subaru $i_p$ band image, showing an offset from the bright blue continuum rim. *Right*: VLA 1.4 GHz continuum contours (65% to 95% of the maximum of 45 $\mu$Jy; Schinnerer et al. 2007) overlaid on the CO(4–3) map showing an excellent correspondence between the molecular gas and the radio continuum, which is presumably tracing star formation activity.

mm at 3.4 ± 0.67 mJy, while the off-line channels in the interferometric observations resulted in a 3 $\sigma$ upper limit of 150 $\mu$Jy at 41.7 GHz (VLA) and a tentative 2.2 $\sigma$ detection of 0.17 ± 0.08 mJy at 83.3 GHz (PdBI). All these values are consistent with the SED fits presented by Capak et al. (2008)[10] and a dust temperature of 30–50 K, typically found in $z \sim 2$ SMGs (Pope et al. 2006; Kovács et al. 2006).

## 4. MASSES AND TYPICAL SMG PROPERTIES

As the molecular gas appears to be thermalized at least up to the CO(4–3) transition as inferred above, its line flux can be used to estimate the CO luminosity [setting $L'_{\rm CO}(J = 4\text{–}3) = L'_{\rm CO}(J = 1\text{–}0)$] and hence the molecular gas mass present in J1000+0234. To derive the CO luminosity $L'_{\rm CO}$ and molecular gas mass $M_{\rm gas}$ we use equations (3) and (4) from Solomon & Vanden Bout (2005) with a conversion factor for $L'_{\rm CO}$ to $M_{\rm gas}$ of $\alpha = 0.8\ M_\odot$(K km s$^{-1}$ pc$^2$)$^{-1}$ derived for local ULIRGs (Downes & Solomon 1998) and used for high-redshift objects (Solomon & Vanden Bout 2005). The observed line flux of $S_{\rm CO(4-3)} = 0.66$ Jy km s$^{-1}$ corresponds to a CO luminosity of $L'_{\rm CO} \sim 3.2 \times 10^{10}\ L_\odot$ or a molecular gas mass of $M_{\rm gas} \sim 2.6 \times 10^{10}\ M_\odot$.

We imaged the red and blue (≈500 km s$^{-1}$ wide) halves of the line emission separately, resulting in a 4.7 $\sigma$ (red) and 3.8 $\sigma$ (blue) emission peak, respectively. The two peaks (Fig. 3) show a spatial shift of ~1″ roughly from northwest to southeast (with a positional uncertainty of ~0.5″). This offset corresponds to ~6.6 kpc at the redshift of J1000+0234, suggesting that the CO emission might be fairly extended. Using this spatial offset between the red- and blueshifted half of the line emission and the line width of ~1000 km s$^{-1}$, we can estimate the dynamical mass of J1000+0234. We use the relation between dynamical mass $M_{\rm dyn}$, velocity width $\Delta v_{\rm FWHM} = v_{\rm rot}(r) \times \sin i/2.4$, and radial extent $r$ of the CO emitting region: $M_{\rm dyn} \times \sin^2 i = 4 \times 10^4 r \Delta v^2_{\rm FWHM}$ (Neri et al. 2003). As the system is likely merging (as discussed below) we include also a factor of 2 for a merging system assuming that the gas has already settled into the new potential (Genzel et al. 2003). The estimated dynamical mass of J1000+0234 is about $1 \times 10^{11}\ M_\odot$ for values of $v_{\rm rot}(r) \times \sin i \sim 1000$ km s$^{-1}$ and a radius $r$ of 3.3 kpc. Thus J1000+0234 has a gas fraction of $M_{\rm gas}/M_{\rm dyn} \sim 25\%$, typical for SMGs (Greve et al. 2005; Tacconi et al. 2006). We would like to caution that the derived offset of ~1″ has significant uncertainties and thus the derived dynamical mass could be overestimated if the separation were smaller.

The properties of J1000+0234 are very similar to the global properties derived for $z \sim 2$ SMGs in terms of molecular gas mass ($\langle M_{\rm gas}\rangle \sim 3 \times 10^{10}\ M_\odot$), extent ($r_{\rm CO} \sim 2$ kpc), CO line width ($\langle {\rm FWHM_{CO}}\rangle \sim 780$ km s$^{-1}$), dynamical mass ($\langle M_{\rm dyn}\rangle \sim 1.2 \times 10^{11}\ M_\odot$), and molecular gas mass fraction (~25%) (Greve et al. 2005). Its estimated current gas consumption timescale of $\tau = M_{\rm gas}/{\rm SFR} \approx 30$ Myr assuming our gas mass and a SFR of $\geq 1000\ M_\odot$ yr$^{-1}$ (Capak et al. 2008) is similar to the gas depletion rates of ~100 Myr found for the $z \sim 2$ SMGs (Tacconi et al. 2008). Taking together the stellar mass of $\geq 10^{10}\ M_\odot$ produced in a recent burst ~7 Myr ago (Capak et al. 2008) and the available gas reservoir and gas consumption timescale derived here, a significant fraction of the stellar mass of a massive elliptical could be produced on a relatively short timescale. Assuming that these recently formed stars will be passively evolving since then, J1000+0234 could turn into a “red and dead” elliptical—like those that are found at $z = 2$ when about 2 Gyr have passed since $z = 4.5$.

[10] The scaling of the SEDs presented in Fig. 4 of Capak et al. (2008) is overestimated by a factor of $10^9$ (P. Capak 2008, private communication).

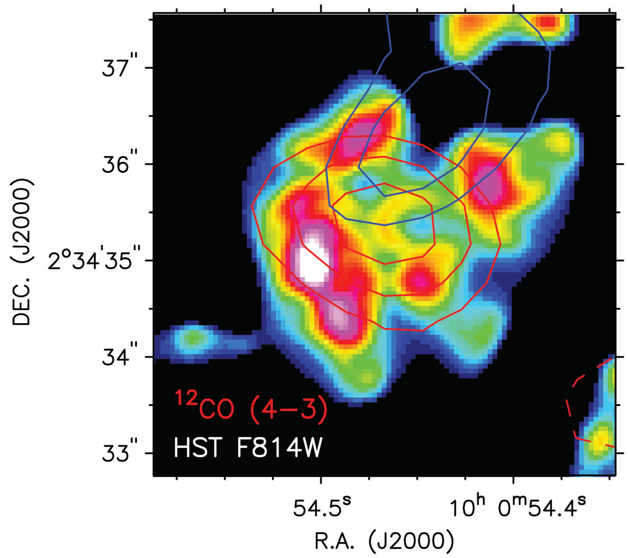


FIG. 3.—Integrated red- and blueshifted CO(4–3) line emission in contours overlaid on the adaptively smoothed *HST* ACS/F814W image of J1000+0234. A motion from southeast to northwest is apparent with an offset of ~1″ between the peaks of the red- and blueshifted emission. The contours start at 2 $\sigma$ in steps of 1 $\sigma$ with 1 $\sigma$ = 0.085 and 0.084 Jy beam$^{-1}$ km s$^{-1}$ for the red- and blueshifted line emission, respectively. The object ~0.5″ west of the CO emission is a foreground galaxy at $z = 1.41$ (Capak et al. 2008).

## 5. EVIDENCE FOR AN ONGOING MAJOR MERGER

The molecular gas emission arises from a region that is highly obscured at the observed optical wavelengths (see Fig. 1 of Capak et al. 2008; Figs. 2 and 3). However, it is coincident with the position of the rest-frame optical and radio emission (Fig. 2). The *HST* ACS image of J1000+0234 (Capak et al. 2008) was adaptively smoothed (Scoville et al. 2000) to enhance the structure present in the blue continuum covered by the F814W filter (Fig. 3). The molecular gas appears to lie next to bright blue continuum emission that is at its eastern side. Ly$\alpha$ emission has also been associated with this bright rim in blue continuum (Capak et al. 2008). The motion of the gas is roughly along a region of higher extinction (compared to the blue western component) running roughly from north to south and shows a larger spatial extent than the blue continuum emission. Note the object west of the gas emission is a foreground galaxy at $z = 1.41$. As already mentioned by Capak et al. (2008) this geometry is very reminiscent of an ongoing merger. As the redshift of the molecular gas is very close to the redshift derived from the Ly$\alpha$ line ($z = 4.542$ vs. $z = 4.547$), it is very likely that both components belong to the same (highly disturbed) system. Both the large FWZI of the CO(4-3) line and the appearance of J1000+0234 in Ly$\alpha$ make an ongoing merger scenario very likely. We derive a conservative estimate of the merging time for J1000+0234 of significantly less than a billion years using the prescription of Kitzbichler & White (2008) for close galaxy pairs with velocities of $v < 3000$ km s$^{-1}$. This timescale is consistent with having a relaxed system at a redshift of $z = 2$.

The expected number of $z = 4$–5 SMGs from the model of Baugh et al. (2005) yields of the order of 10–20 such sources within the 2 $deg^2$ COSMOS field. As J1000+0234 was originally identified as a Lyman break galaxy via its *V*-band drop (Capak et al. 2008; Carilli et al. 2008), this suggests that UV emission can be detectable from ongoing major mergers at these redshifts. We have identified 4 additional *V*-band dropout LBGs with 4 $\sigma$ radio detections (Carilli et al. 2008) that could also be SMGs at this redshift. An inspection of their optical appearance in the *HST* ACS data shows that two of them also have a disturbed geometry. This suggests that there could be more objects sharing properties of both the SMG and LBG population at $z > 4$ and J1000+0234 might therefore provide an important link between the SMG and LBG populations at high redshifts.

The case of J1000+0234 shows that (at least some) $z > 4$ SMGs can have very similar properties to their well-studied low redshift ($z \sim 2$) counterparts, that major mergers with very large SFRs are likely present at $z = 4.5$, and that these systems might be the precursors of elliptical galaxies found at the red sequence at a redshift of $z = 2$.

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*Facilities*: IRAM:30m, IRAM:Interferometer, VLA

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